Teaching solid-state physics in materials science without quantum mechanics

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Abstract: Based on many years of teaching solid-state physics and university physics, the methods for teaching solid-state physics well in a materials science major without a quantum mechanics or quantum statistics course are summarized.

Keywords: Quantum Mechanics, Solid-State Physics, Teaching Methods

1. Introduction

Solid - state physics is an important basic course for materials science majors. Since the department of materials began to enroll graduate students in 1982, solid - state physics has always been offered as a degree - granting course. As is known to all, quantum mechanics, quantum statistics and college physics are the foundations for learning solid - state physics. Our students have only studied college physics, and they have had little contact with the content of quantum mechanics and no exposure to quantum statistics. Solid - state physics is the discipline that studies the structure of solids, their composition and the laws governing the interactions between the constituent particles, and clarifies their properties and applications. It can reveal the microscopic essence of the macroscopic properties of solids. Quantum mechanics, which focuses on the laws governing the motion of microscopic particles, is a powerful tool for learning solid - state physics. Students are accustomed to classical macroscopic laws. Faced with the invisible and intangible microscopic substances, they feel at a loss. The study of quantum mechanics involves the use of a great deal of mathematical knowledge and requires students to have a good foundation in physics as well as the ability to think abstractly. As a result, they find it extremely difficult and have trouble accepting the methods used in quantum mechanics to deal with problems. Therefore, how to supplement students of materials departments in engineering colleges with knowledge of quantum mechanics without increasing class hours and make the teaching suitable for the characteristics of materials departments is a question worthy of exploration. After years of teaching practice, we have realized that although solid - state physics is a theoretical course that is abstract and hard to understand, as long as we start from the actual situation of the materials department and teach students according to their aptitude, students can still grasp this course relatively well.

2. Clarify the importance of solid-state physics for the materials major

2.1. The Importance of the course "Solid-State Physics" and its teaching objectives

Our university aims to establish itself as a teaching and research - oriented institution, dedicated to cultivating innovative and versatile talents with a comprehensive and harmonious development of abilities, knowledge, quality, and personality. As an important professional basic course in the materials department, "Solid - State Physics" plays a crucial role in developing the theoretical knowledge and scientific literacy of students majoring in materials. Therefore, the goal of offering this course is not only to lay a solid foundation for students' specialized studies but also to help them understand and even master cutting - edge scientific knowledge. We are also committed to consciously fostering students' innovative spirit and practical abilities and stimulating their strong interest in and enthusiasm for scientific exploration. Given that "Solid - State Physics" is a vital basic course for graduate students, its teaching effectiveness, the depth

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and quality of the course content have a decisive impact on students' subsequent specialized education. As a student in the materials department, it is essential to recognize the significance of this course.

2.2. Teaching methods for the course "Solid-State Physics" and suggestions for student learning

Solid-state physics is a theoretical course that is difficult to learn. If students of the materials department do not understand the relationship between this course and their specialized courses, and are not aware of the impact of the development of solid-state physics in the past 20 years on related sciences, and if the teaching is just confined to talking in generalities, it will be hard for students to delve deeper into the subject. Therefore, when we give the introductory lecture, we should first introduce the development history of solid-state physics and the changes that each of its developmental steps has brought to science and technology. For example, in the mid-19th century, Bravais summarized that crystal structures have periodic features. In 1912, Laue first pointed out that crystals could act as X-ray diffraction gratings. The analysis of crystal structures through Laue spots strongly confirmed the theory of spatial lattices. The development of quantum mechanics has enabled people to gain a deep understanding of the motion laws of microscopic particles inside crystals. From macro to micro, from phenomena to essence, people have come to recognize the quantization of lattice vibrations. Based on the theory of free electrons in metals, solid-state quantum theory has been developed, and the band theory of solids has been gradually established, proposing the existence of semiconductors between conductors and insulators. Later, with the various material needs of society, high-temperature-resistant, lightweight, high-strength, and radiation-resistant aviation materials were developed, as well as super-hard materials like diamond and high-performance single crystals. New solid materials are developing towards composite materials, nanomaterials, and smart materials that can sense changes in the external environment or parameters and have driving functions. Solid-state physics has made great contributions to the discovery and use of new solid materials. It is not only important for the physics major but also the professional foundation for mastering materials science and electronics. The electrical, thermal, and optical properties of solid materials are all related to their microstructures. The simplest example is that both diamond and graphite are composed of carbon atoms, but diamond is very hard while graphite is soft. This is because they have different structures: one has a diamond structure, and the other has a layered structure. Structure determines properties. Only in this way can students understand that with the rapid development of science and technology, some current engineering and technical problems, especially in the field of materials, can only be solved with the knowledge of solid-state physics. As future engineering and technical talents, only by mastering the basic theories of solid-state physics can students better grasp professional knowledge, lay a solid foundation for future work, and thus enhance their consciousness and enthusiasm for learning.

3. To learn solid-state physics well, one must master the powerful tool of quantum mechanics

Solid-state physics is a course with strong theoretical aspects, requiring a solid foundation in physics and advanced mathematics. Students in the materials department typically have only a general physics background, and they haven't studied quantum mechanics or statistical physics, both of which are involved in the course. The textbook we use is the basic part of the first volume of "Solid State Physics" by Fang Junxin and Lu Dong. This can lead to students lacking sufficient basic knowledge in the early stages. Advanced mathematics and statistical physics can be integrated and supplemented during the lectures. The biggest issue, however, is quantum mechanics. Core content such as specific heat theory, electronic theory, and band theory of solids require extensive knowledge of quantum mechanics. The band structure is the result of solving the Schrödinger equation for a many - electron system. Some teachers only provide the results of the band theory without explaining the process of derivation. This can lead to students knowing what happens but not why, lacking persuasiveness and a profound understanding of the conclusions. If a large amount of time is spent supplementing quantum mechanics, it will shift attention and dilute the learning of the main content. It will also cause tension in the class hours, making it difficult to complete the teaching tasks within the prescribed time. Some students with poor foundations in physics and advanced mathematics may not understand the concepts clearly and in a timely manner. They may find the course

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boring and lose confidence the more they study. Supplementing quantum mechanics knowledge well is the key to learning solid - state physics in depth.

4. How to optimize the teaching content to supplement quantum mechanics knowledge [3]

4.1. The compilation of "Solid-State Physics learning guide" and the teaching methods

According to the students' level, the author has written the book "Solid - State Physics Learning Guide". The teaching difficulties and key points of each chapter are presented in the form of questions. Students read the textbook, refer to relevant materials, and combine the review questions to understand and sort out the content of each chapter, thus mastering the key points and difficulties of each chapter. Due to the limitation of class hours, some content can be omitted, such as the binding of crystals and the defects of crystals. Students have learned these in the basic courses of materials science. The outline is given and students are encouraged to study these parts by themselves in combination with the thinking questions. These parts will be tested in the final exam. In this way, the teaching can be detailed where necessary and brief where possible. Guiding students in independent learning not only saves class hours but also improves their self - learning and independent thinking abilities.

4.2. Key points and methods in solid-state physics teaching

The author believes that when teaching solid-state physics, it is essential to clarify the relationship between physical laws, mathematical derivations, and the additional knowledge of quantum mechanics that is needed. Full use should be made of mathematical tools, and the physical essence of each formula must be clearly explained. For students in the materials department, important derivations should be thoroughly discussed in class, while avoiding difficulties that may arise from mathematical operations as much as possible. The focus must be on the establishment of physical models and the thought process of the derivation, clarifying the concepts, principles, and methods of problem - solving in solid - state physics itself. Students should be enabled to grasp the essentials and learn actively, without getting lost in complicated mathematical derivations. Simple models and mathematics should be used to explain problems whenever possible. The physical meaning of the derivation results should be clearly discussed with the students. When deriving, the conclusion and steps of the proof can be given first and then the derivation can be carried out, or the conclusion can be used first and then the derivation can be done. For example, the properties of Bloch's theorem can be used first, and the proof of the theorem can be worked out with the students in the exercise class. For difficult lessons, more interaction between teachers and students is needed, rather than the teacher speaking eloquently and the students listening in confusion. The teaching process should be conducted in an heuristic way, guiding students to think about problems based on the discovery of issues, teaching students scientific ways of thinking, so that students can learn actively and achieve better learning results.

4.3. The supplement and application of quantum mechanics content

How to supplement the content of quantum mechanics: To avoid being boring and not overshadowing the main subject, some necessary content of quantum mechanics is interspersed in various chapters and explained in combination with relevant content (such as the quantum theory of lattice vibrations - introducing the concept of phonons). When it comes to band theory, it is necessary to solve the Schrödinger equation for a many - electron system. We have added 4 - 5 class hours of quantum mechanics here. The focus is on explaining the basic methods of quantum mechanics in dealing with problems and some basic conclusions obtained. First, the wave - particle duality of material particles and the concept of probability waves are introduced, and then the Schrödinger equation is introduced. By studying the solution of one - dimensional stationary problems, we can understand the basic methods of quantum mechanics in dealing with problems and obtain some basic conclusions. The one - dimensional linear harmonic oscillator is briefly introduced. The focus of the lecture is to guide students to make the transition from classical to quantum and to understand the differences in research methods between classical and quantum. The

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physical quantities studied in quantum mechanics are discrete, such as the energy obtained from one-dimensional stationary states is discrete, while classical physical quantities are continuous. To complete the leap in students' understanding, let them taste the "quantum" flavor, and then introduce the mechanical quantities in quantum mechanics (commutation relations), states and representations of mechanical quantities, and finally explain the perturbation of stationary states and degenerate perturbation. This part involves a lot of mathematical derivation. We try to avoid it as much as possible, explain the idea concisely, and only derive when necessary. Clarify the physical meaning of the conclusions, and being able to use them is enough. This can help students break through the barriers of difficult mathematical derivation and the fear it generates.

Learn the methods for dealing with problems in quantum mechanics: Establish a physical model, solve the mathematical equations established by the model, and reveal the obtained results in the language of physics. The key is that everyone must abandon classical concepts and accept the unusual results of quantum mechanics. As an application of the above quantum mechanics theory, the band theory is then discussed. The lecture notes with supplementary content are distributed to students for easy reference. Practice has proved that the effect is good.

5. Reform of teaching methods and assessment modes

Solid - state physics not only has abstruse concepts (such as reciprocal lattices) but also has complex graphics, spatial transformations and cumbersome theoretical derivations. To help students digest what they have learned, we arrange four to five problem - solving sessions in coordination with the content of classroom lectures. First, the teachers will make a brief summary of the content they have taught, pointing out the key points and requirements. Then, they will give some typical problems centering on the key and difficult points. Under the guidance of the teachers, the students will first propose solutions, which the teachers will help them to complete or work together with them to finish. Practice has proved that this method is very effective. Some previously unclear concepts can also be clarified through the discussion of specific problems, which is better than the teacher's repeated lectures. Since the conclusions are reached by the students through their own thinking and problem - solving under the guidance of the teacher, they are more easily acceptable to the students and leave a deeper impression.

Multimedia teaching is adopted in class to simultaneously demonstrate complex solid structures and physical processes that are hard to describe in words. This lowers the teaching difficulty, increases the amount of information and saves class hours. For example, the crystal structure and Brillouin zones are vividly and stereoscopically displayed through video animations, which makes it easier for students to accept. More applications closely related to the major are introduced to increase students' interest in learning. For example: the development and application of crystals, new types of composite materials, nanomaterials; when discussing X - ray diffraction, the crystal structure is determined according to the diffraction spectrum of the materials to be measured in the laboratory; when talking about crystal binding, new - type corrosion - resistant materials (NiAl), covalent C60, high - temperature superconducting materials, etc. are introduced, so that students can really feel that structure determines properties and solid - state physics has a theoretical guiding role in materials science.

In terms of assessment, the written exam accounts for 70 points, while daily classroom performance and major assignments account for 30 points. The whole process of guiding and monitoring students' learning can better reflect their real abilities and overall quality and is also welcomed by the students.

6. Conclusion

Combining the actual situation of students in the materials department and through years of teaching practice, we have integrated the teaching content and reformed the teaching methods and means. This has mobilized students' initiative in learning. A highly theoretical course has become vivid and no longer complicated and tedious. Students' interest in learning has been increased, and good teaching results have been achieved. Through the teaching of solid - state physics, students not only acquire theoretical knowledge, but also improve their comprehensive abilities and cultivate their scientific spirit of exploration. Society today is in great need of such versatile talents.

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